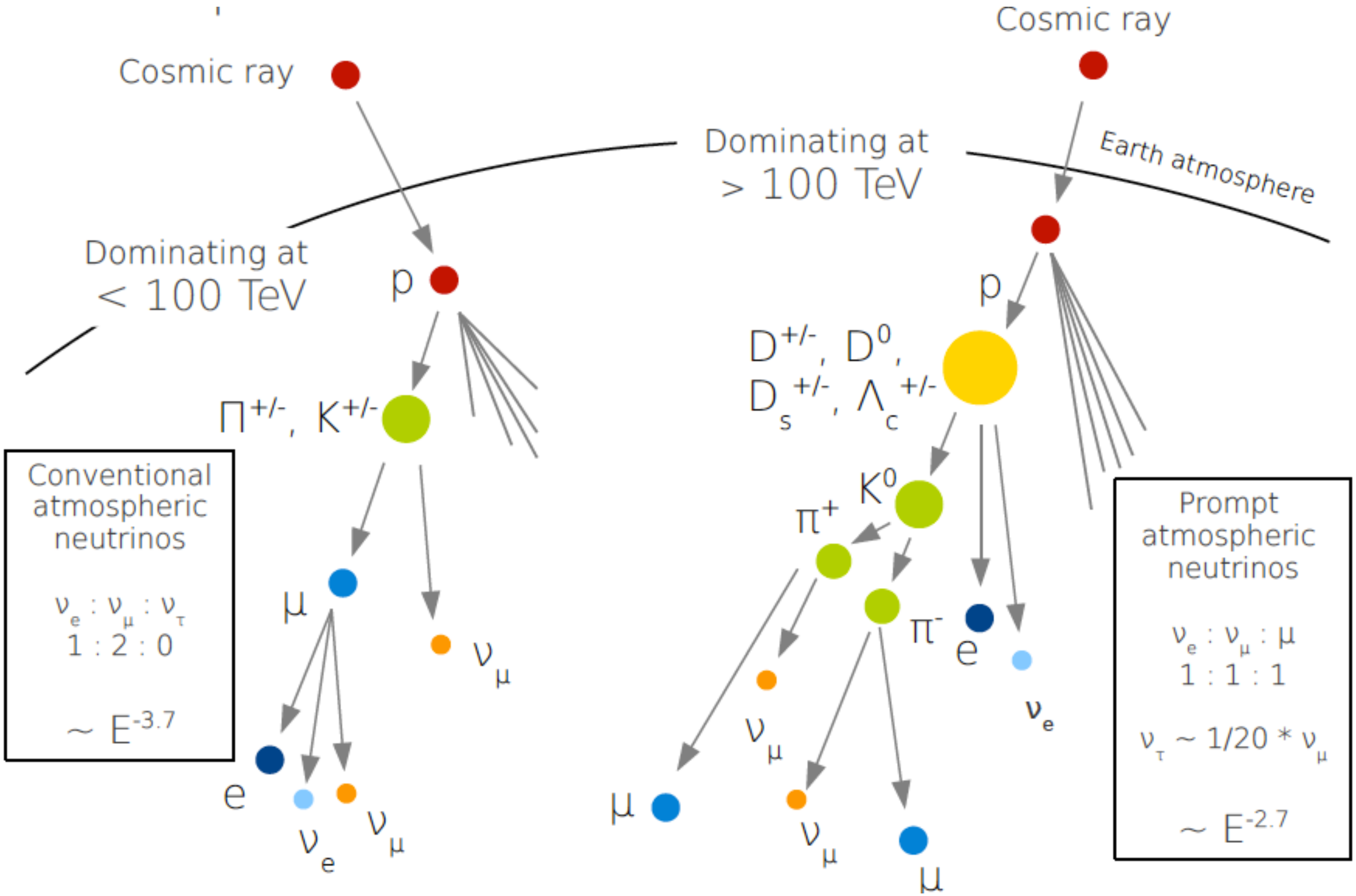


Courtesy: Anne Schukraft

Moving *forward* with atmospheric charm

Rhorry Gauld || Juan Rojo || Luca Rottoli || Subir Sarkar || **Jim Talbert**

DESY, Hamburg

12 December 2016 || Helmholtz Institute, Mainz

arXiv:1506.08025 + 1511.06346

Prompt vs. conventional flux

- The energy spectrum from semi-leptonic decay products depends on a hadronic '**critical energy**', *below* which the **decay probability** is **> interaction probability**:

$$\epsilon_h = \frac{m_h c^2 h_0}{c\tau_h \cos\theta} \qquad \begin{aligned} \epsilon_{\pi^\pm} &= 115\ [GeV] \\ \epsilon_{K^\pm} &= 850\ [GeV] \end{aligned}$$

- For **pions & kaons**, this critical energy is low (decay length is long) hence the leptonic energy spectrum is soft. For **charmed mesons**, the critical energy is high … they **decay *promptly*** to highly energetic leptons:

$$\begin{aligned} \epsilon_{D^0} &= 9.71 \times 10^7\ [GeV] \\ \epsilon_{D^\pm} &= 3.84 \times 10^7\ [GeV] \\ \epsilon_{D_s^\pm} &= 8.40 \times 10^7\ [GeV] \\ \epsilon_{\Lambda_c} &= 24.4 \times 10^7\ [GeV] \end{aligned}$$

- The atmospheric neutrino flux from the decay of pions & kaons is the '**conventional flux**,' whereas that from charm decay is called the '**prompt flux**'

Previous calculations

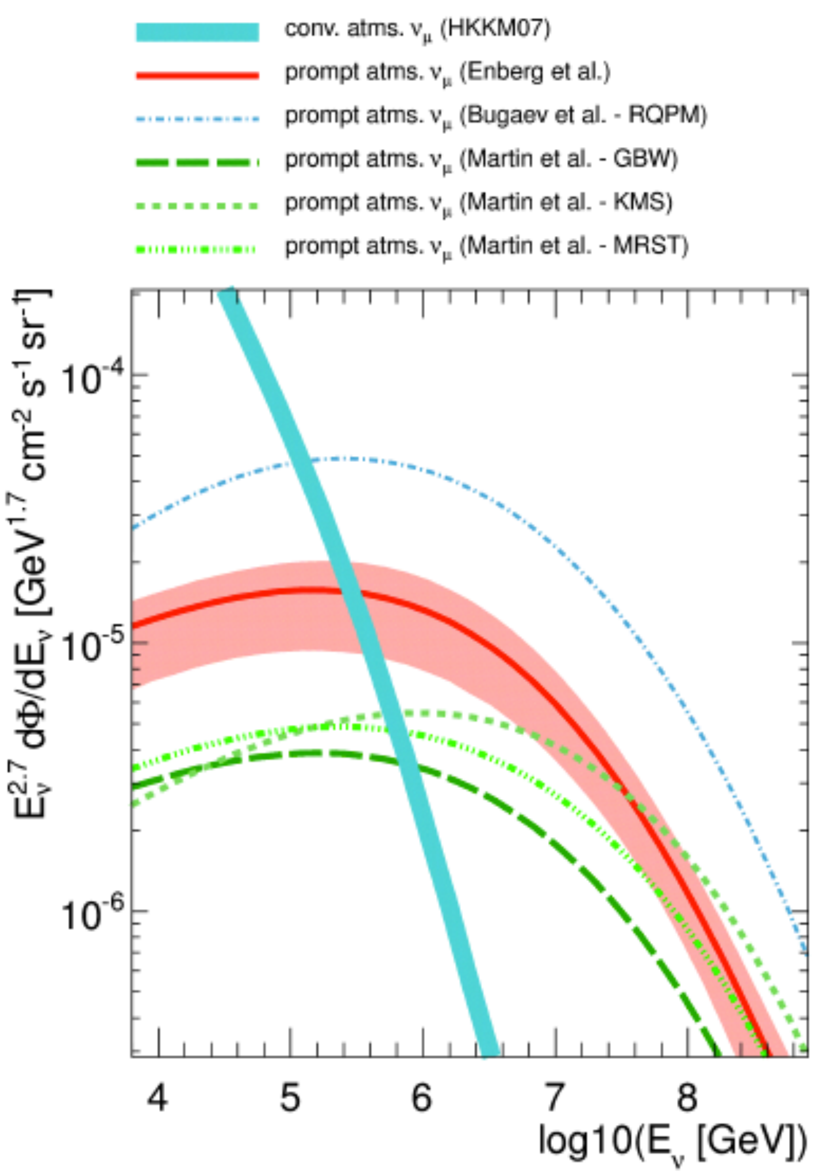
- **Volkova**, Sov. J. Nucl. Physics 12 (1980) 784
- **Bugaev, Naumov, Sinegovksy, Zaslavskaya**, Il Nuovo Cimento C **12** (1989) 41
- **Lipari**, Astroparticle Physics **1** (1993) 195
- **Thunman, Ingelman, Gondolo** (TIG), Astroparticle Physics **5** (1993) 309
- **Pasquali, Reno, Sarcevic** (PRS), Physical Review D**59** (1999) 034020
- **Gelmini, Gondolo, Varieschi** (GGV1), Physical Review D**61** (2000) 036005
- **Gelmini, Gondolo, Varieschi** (GGV2), Physical Review D**61** (2000) 056011
- **Martin, Ryskin, Stasto** (MRS), Acta Physica Polonica B**34** (2003) 3273
- **Enberg, Reno, Sarcevic** (ERS), Physical Review D**78** (2008) 043005
- **Bhattacharya, Enberg, Reno, Sarcevic, Stasto** (BERSS), arXiv:1502.01076
- **Garzelli, Moch, Sigl** (GMS), arXiv:1507.01570
- **Gauld, Rojo, Rottoli, Sarkar, Talbert** (GRRST), arXiv:1511.06345
- **Bhattacharya, Enberg, Jeong, Kim, Reno, Sarcevic, Stasto**, arXiv:1607.00193
- **PROSA Collaboration**, arXiv:1611.03815

Calculating the prompt flux of atmospheric neutrinos requires a synthesis of QCD, cosmic ray physics, and neutrino physics

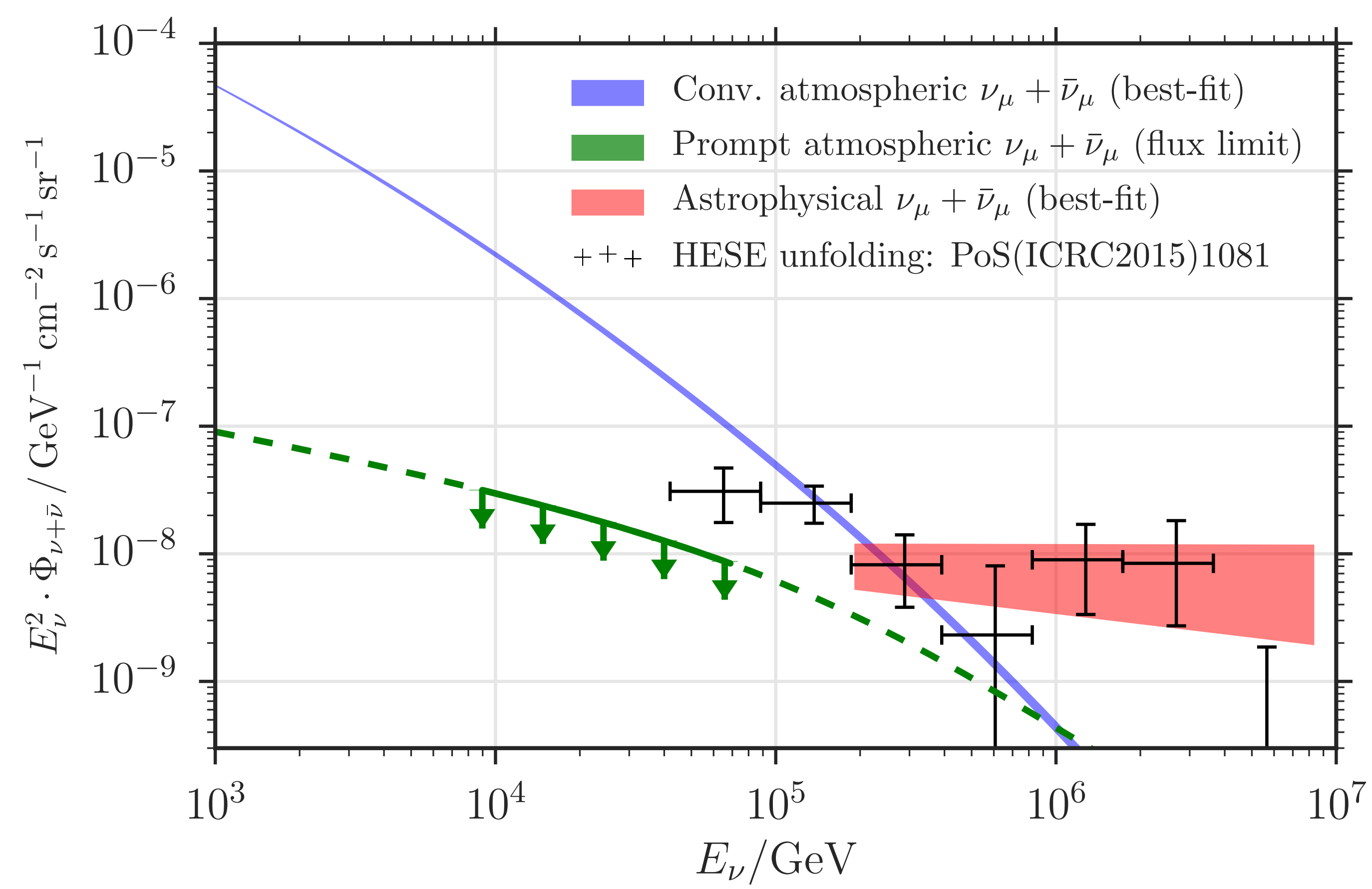
Where are the prompt neutrinos?

- The flux of prompt neutrinos is *harder* than that of conventional neutrinos, and was predicted to *dominate* the total atmospheric flux at energies above ~10^{5-6} GeV

(Sebastian Schonen, IPA 2015)



No prompt flux seen so far … but an astrophysical signal with ~similar spectrum has been discovered!

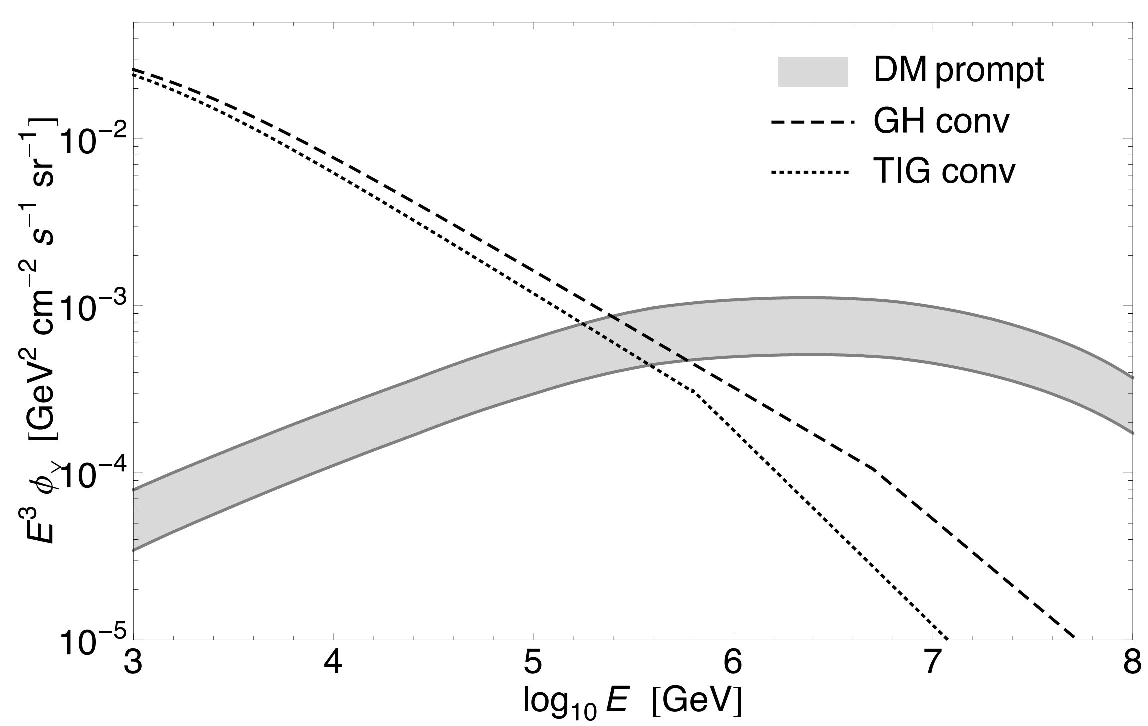


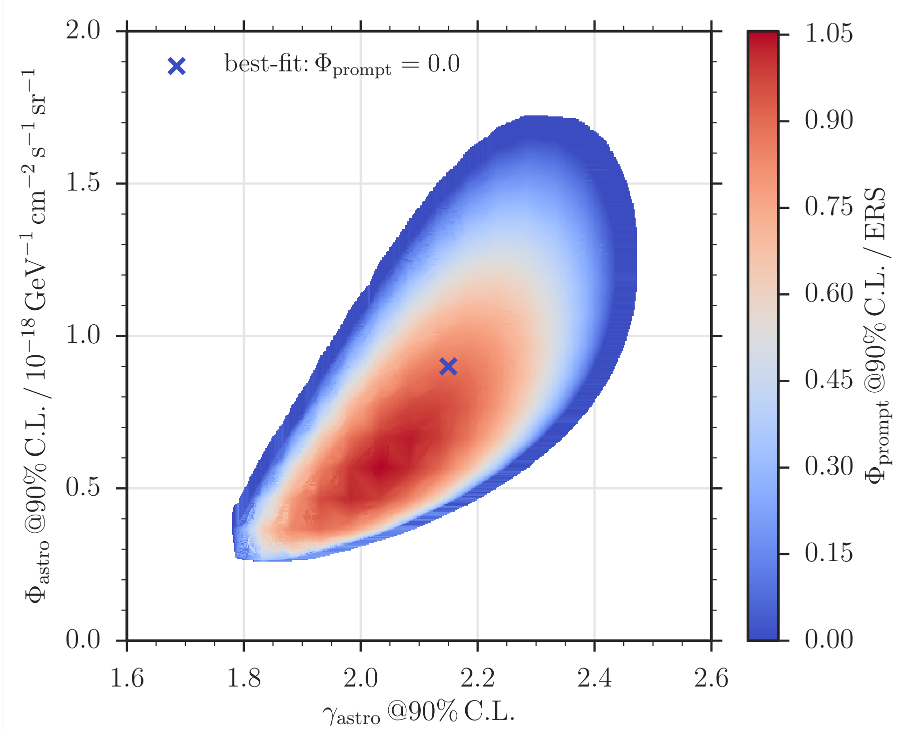
IceCube - 1607.08006

- The conventional background is well understood as it has been calibrated against many observations … uncertainties in charm production make the prompt flux less so but it is the most important background for the expected astrophysical flux!

Tension with ERS benchmark?

arXiv:hep-ph/1607.08006
arXiv:astro-ph/1410.1749
arXiv:hep-ph/0806.0418





Parameter	Best-fit value	No. of events
Penetrating μ flux	$1.73 \pm 0.40\,\Phi_{\mathrm{SIBYLL+DPMJET}}$	30 ± 7
Conventional ν flux	$0.97^{+0.10}_{-0.03}\,\Phi_{\mathrm{HKKMS}}$	280^{+28}_{-8}
Prompt ν flux	$< 1.52\,\Phi_{\mathrm{ERS}}$ (90% CL)	< 23
Astrophysical Φ_0	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ GeV^{-1} cm^{-2} sr^{-1} s^{-1}	87^{+14}_{-10}
Astrophysical γ	2.46 ± 0.12	

2014

Model	Flux limit
ERS (H3p)	1.06
GMS (H3p)	≈ 2.9
BERSS (H3p)	≈ 3.0
GRSST (H3p)	≈ 3.1

2016

Even stronger limit of ~0.5×ERS @ 90% C.L. from combined IC59 + IC79 + IC86 data?

(Sebastian Schonen, IPA 2015)

Tracing a particle through the atmosphere

- The flux of particle j can be generically written as:

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{dec}} + \sum S(k \to j)$$

- This depends on the '**slant depth**' X measuring the atmosphere traversed:

$$X(l,\theta) = \int_l^\infty \rho(H(l^{'},\theta)dl^{'} \qquad H(l,\theta) \simeq l\cos\theta + \frac{l^2}{2R_0}\sin^2\theta$$

- We adopt a simple **isothermal model** of the atmosphere:

$$\rho(H) = \rho_0 e^{-\frac{H}{H_0}}$$

$$\rho_0 = 2.03 \times 10^{-3} \quad [\frac{g}{cm^3}]$$

$$H_0 = 6.4 \quad [km]$$

- Such that sample values of X are:

$$X = 0 \; [\frac{g}{cm^2}] \;\; (space) \qquad X = 1300 \; [\frac{g}{cm^2}] \;\; (\theta = 0)$$

$$X = \infty \; [\frac{g}{cm^2}] \;\; (ground) \qquad X = 36000 \; [\frac{g}{cm^2}] \;\; (\theta = \frac{\pi}{2})$$

Cascade formalism: sources & Z-moments

$$S(k \to j) = \int_E^\infty \frac{\phi_k(E_k^{'})}{\lambda_k(E_k^{'})} \frac{dn(k \to j; E^{'}, E)}{dE} dE^{'}$$

- Under reasonable assumptions, the S-moments simplify:

$$S(k \to j) = \frac{\phi_k}{\lambda_k}\ Z_{kj}$$

- For particle **production**:

$$Z_{kh} = \int_E^\infty dE^{'} \frac{\phi_k(E', X, \theta)}{\phi_k(E, X, \theta)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(kA \to hY; E', E)}{dE}$$

$$\frac{dn(pA \to hY; E', E)}{dE} = \frac{1}{\sigma_{pA}(E')} \frac{d\sigma(pA \to hY; E', E)}{dE}$$

- For particle **decay**:

$$Z_{h\to l} = \int_E^\infty dE^{'} \frac{\phi_h(E', X)}{\phi_h(E, X)} \frac{d_h(E)}{d_h(E')} \frac{dn(h \to lY; E', E)}{dE}$$

$$\frac{dn(h \to lY; E', E)}{dE} = \frac{1}{\Gamma} \frac{d\Gamma}{dE}$$

Atmospheric nucleon flux

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY) = -\frac{\phi_N}{\lambda_N} + Z_{NN}\frac{\phi_N}{\lambda_N}$$

Assume a **factorization** of fluxes ⟶ $\phi_k(E,X) = \phi_k(E)\phi_k(X)$

Define the **interaction** length ⟶ $\lambda_N(E) = \dfrac{A}{N_0\sigma_{pA}(E)}$

Define the **attenuation** length ⟶ $\Lambda_N = \frac{\lambda_N}{(1-Z_{NN})}$

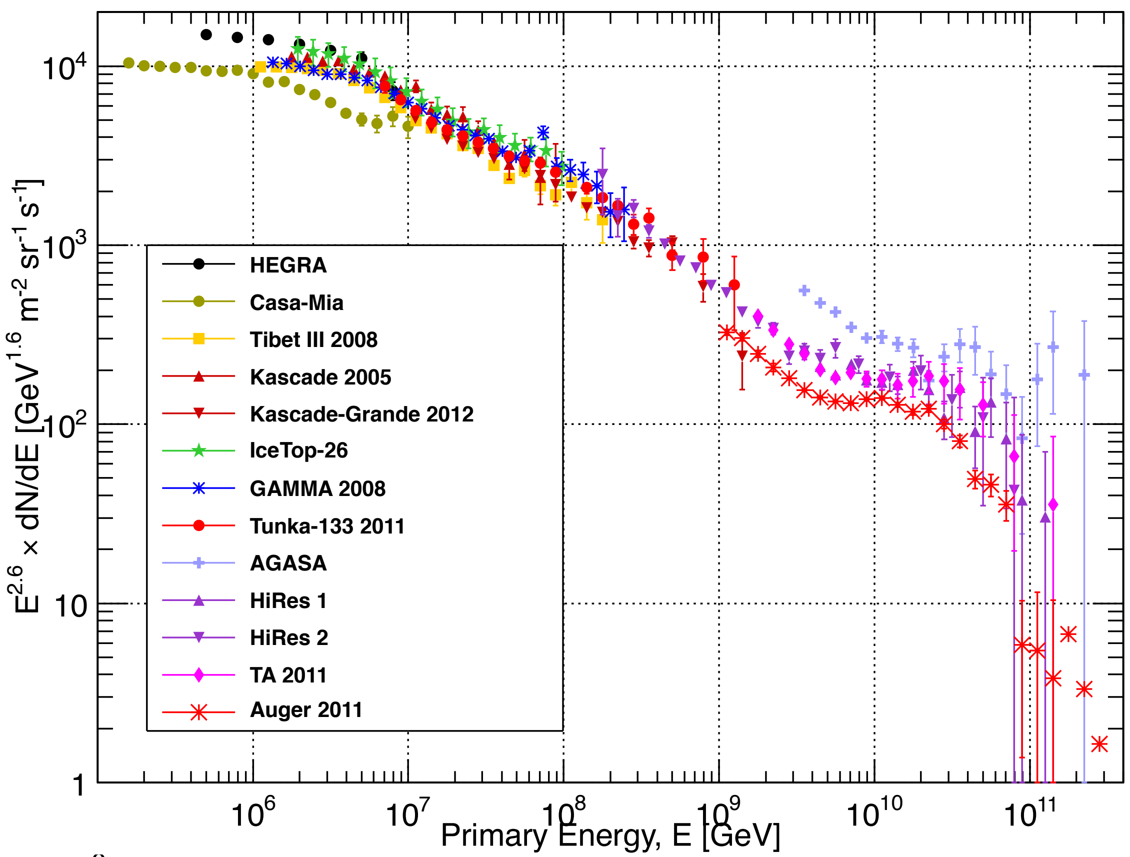
$$\frac{d\phi_N}{dX} = \frac{\phi_N}{\lambda_N}(Z_{NN}-1) \to \frac{d\phi_N}{dX} + \frac{\phi_N}{\lambda_N}(1-Z_{NN}) = 0$$

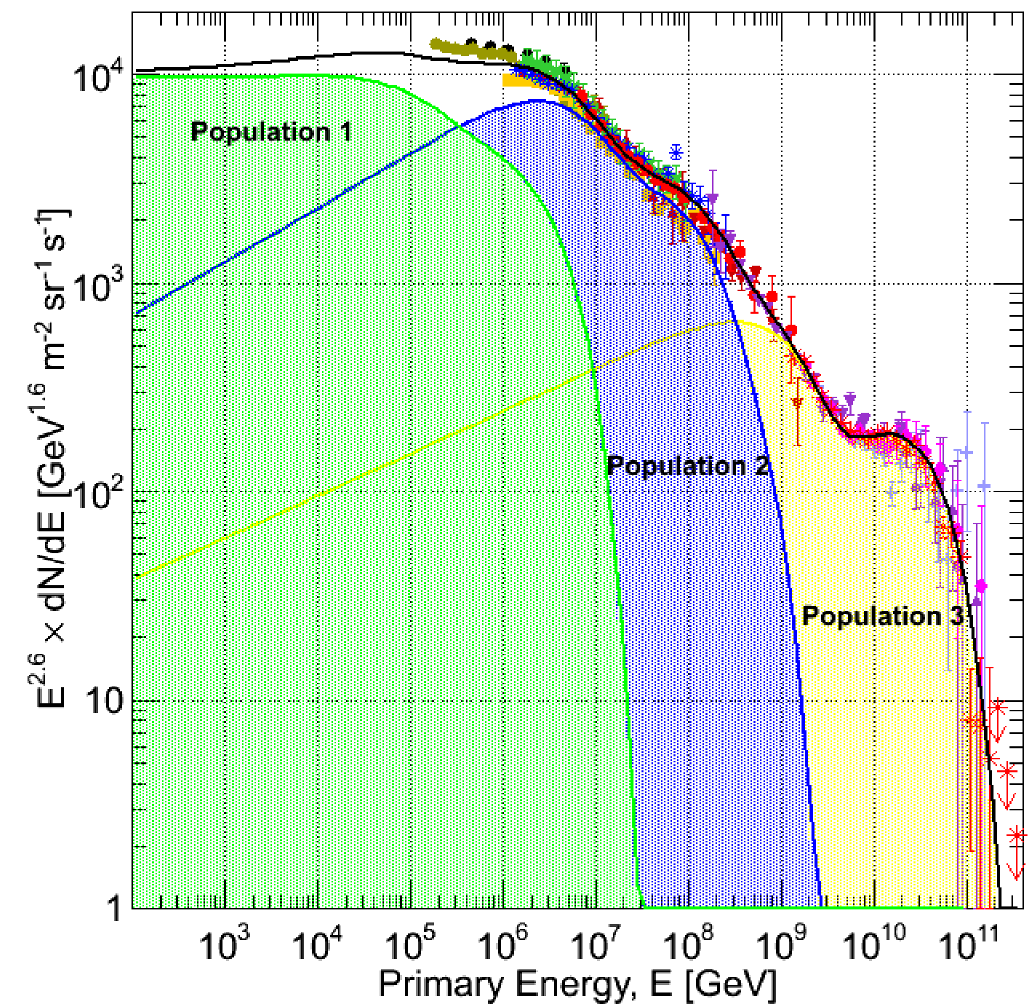
$$\phi_N = \phi_N^0(E)\; e^{-\frac{X}{\Lambda_N}}$$

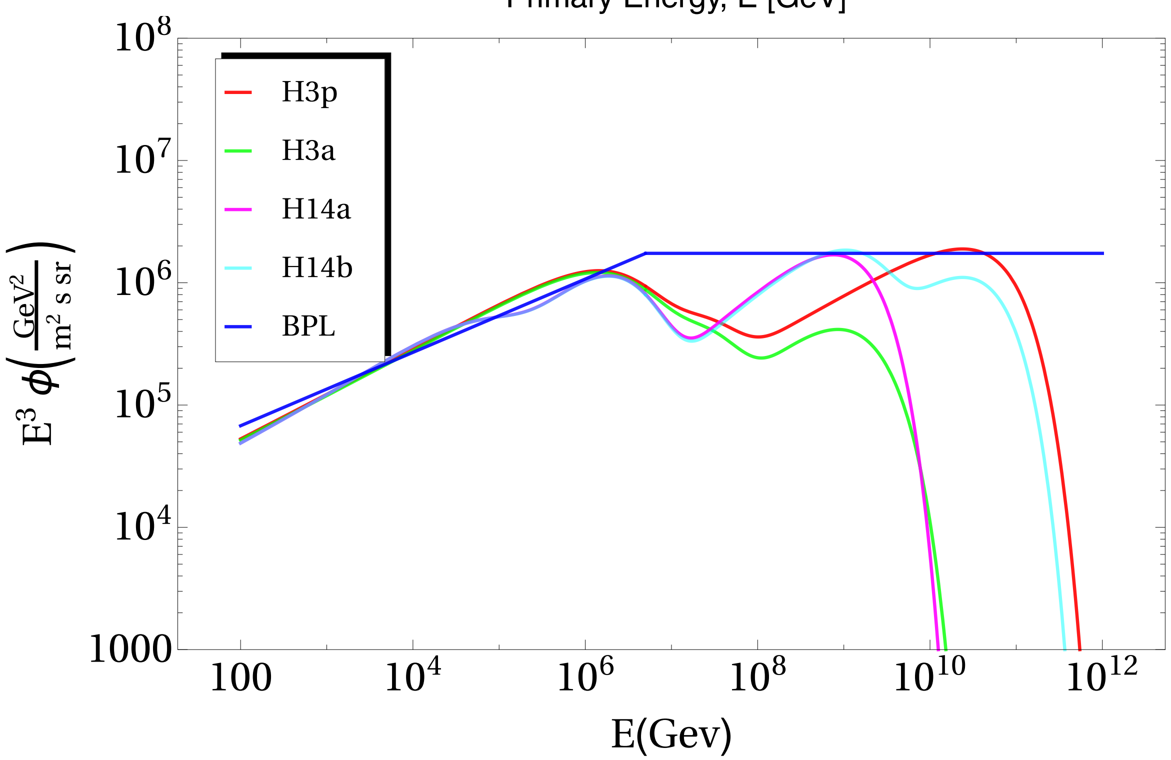
What constitutes this primary nucleon flux?

Gaisser *et al*. fluxes: $\phi_N^0(E)$

arXiv:astro-ph/1111.6675
arXiv:astro-ph/1303.3565







$$\phi_N^0(E) = \begin{cases} 1.7\ E^{-2.7} & for\ E < 5 \times 10^6\ GeV \\ 174\ E^{-3} & for\ E > 5 \times 10^6\ GeV \end{cases}$$

$$\phi_i(E) \ = \ \Sigma_{j=1}^{3}\, a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

Lepton flux @ detector

1. $\frac{d\phi_p}{dX} = -\frac{\phi_p}{\lambda_p} + Z_{pp}\frac{\phi_p}{\lambda_p}$

2. $\frac{d\phi_h}{dX} = -\frac{\phi_h}{\rho d_h(E)} - \frac{\phi_h}{\lambda_h} + Z_{hh}\frac{\phi_h}{\lambda_h} + Z_{ph}\frac{\phi_p}{\lambda_p}$

3. $\frac{d\phi_l}{dX} = \sum_h Z_{h\to l}\frac{\phi_h}{\rho d_h}$

Full series of **cascade equations**, from incoming cosmic ray nucleons to final state leptons

$$\phi_l|_{low} = \phi_p(E)\ Z_{h\to l}^{low}\ \frac{Z_{ph}}{(1-Z_{pp})}$$

$$\phi_l|_{high} = \frac{Z_{h\to l}\epsilon_h}{E}\frac{Z_{ph}\phi_p(E)}{(1-Z_{pp})(1-\frac{\Lambda_p}{\Lambda_h})}\ln\frac{\Lambda_h}{\Lambda_p}$$

Geometric Interpolation:

$$\phi_l = \sum_h \frac{\phi_l^{low}\phi_l^{high}}{\phi_l^{low}+\phi_l^{high}}$$

- Our final flux includes all (interpolated) contributions from **charmed hadrons**

The QCD input: Z_{ph}

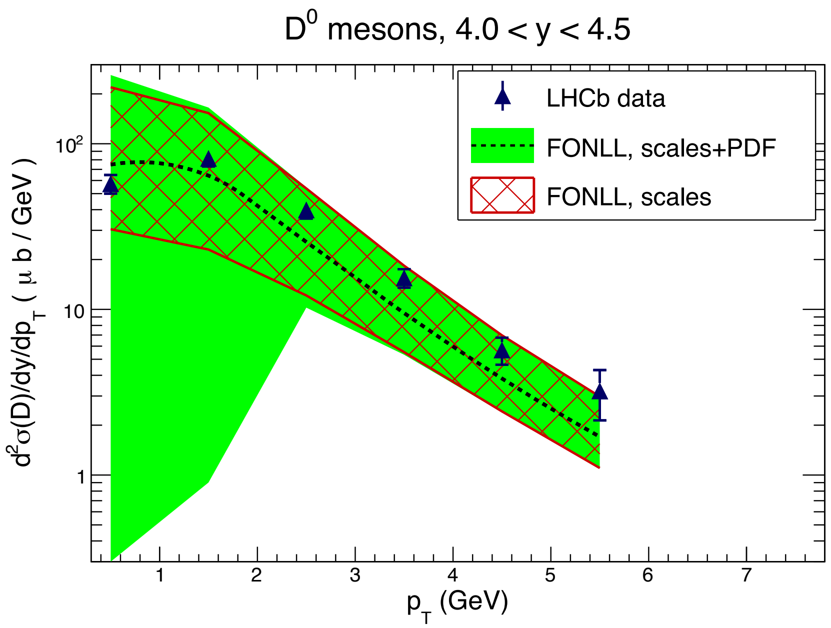
$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

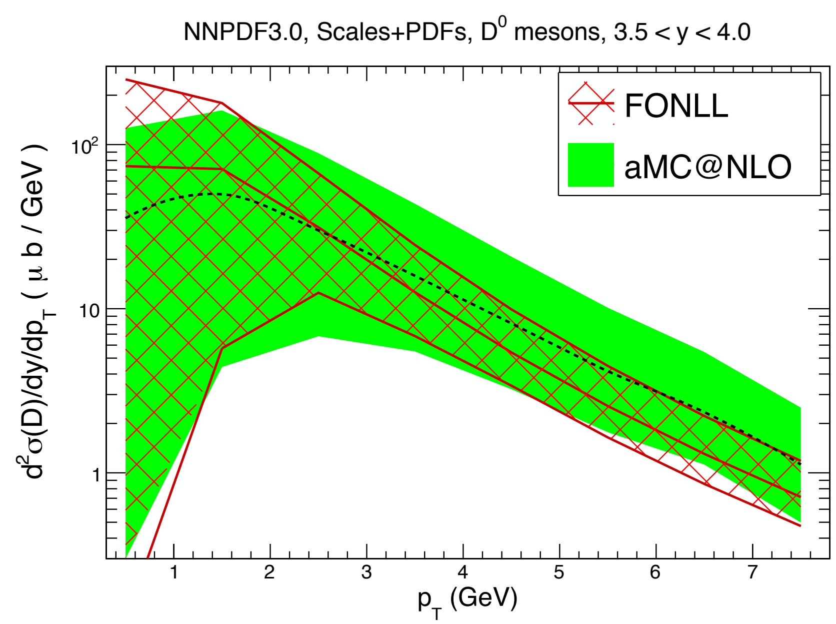
- The **differential cross-section** can be calculated in a variety of formalisms, e.g. the 'colour dipole model' of ERS which is empirical (hard to estimate uncertainties)
- However, there is no evidence that **perturbative QCD (with DGLAP evolution)** *cannot* describe charm production data for the entire kinematical region of interest, hence our calculation is performed with **NLO+PS Monte-Carlo event generators**
- Boosting from CM to the rest frame of the (atmospheric) fixed target, one finds:

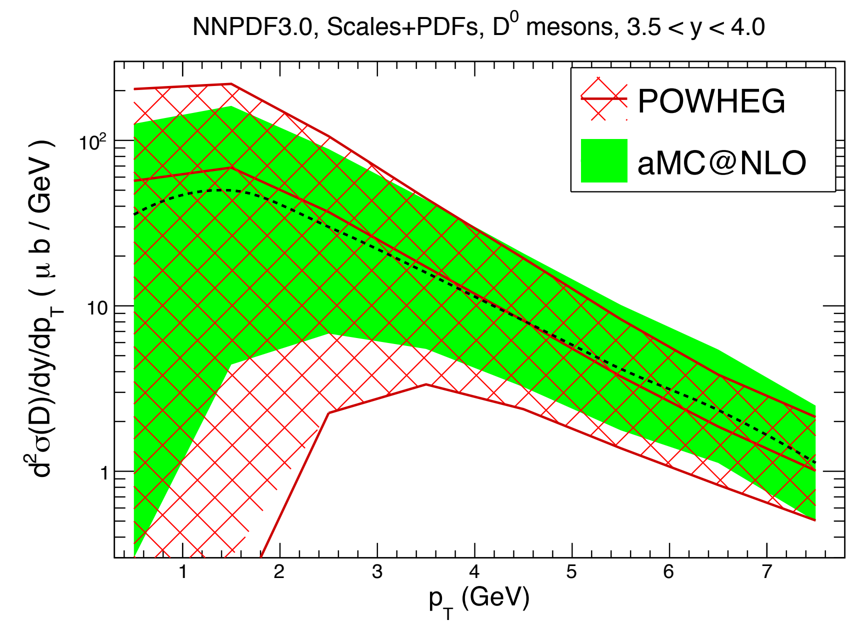
$$\sqrt{s} = 7\ [TeV] \longleftrightarrow E_b = 2.6 \times 10^7\ [GeV]$$

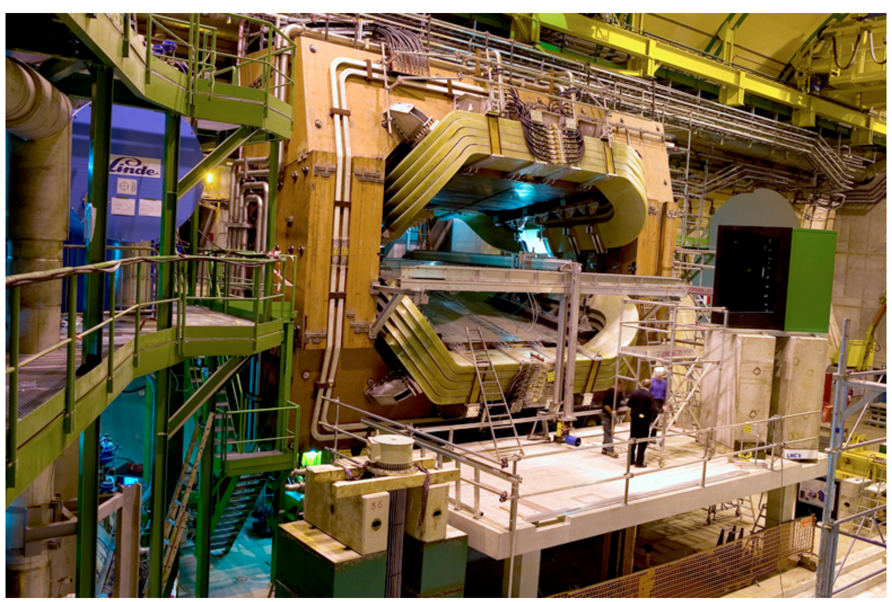
- Thus there is **complementarity with LHC physics**. We will predict the prompt neutrino flux at energies **up to $10^{7.5}$ GeV** … at these energies, the charm production cross section is dominated by **gluon fusion**, hence we are sensitive to the behavior of the **gluon PDF** (parton distribution function) **at small-*x***

Forward charm production & LHCb





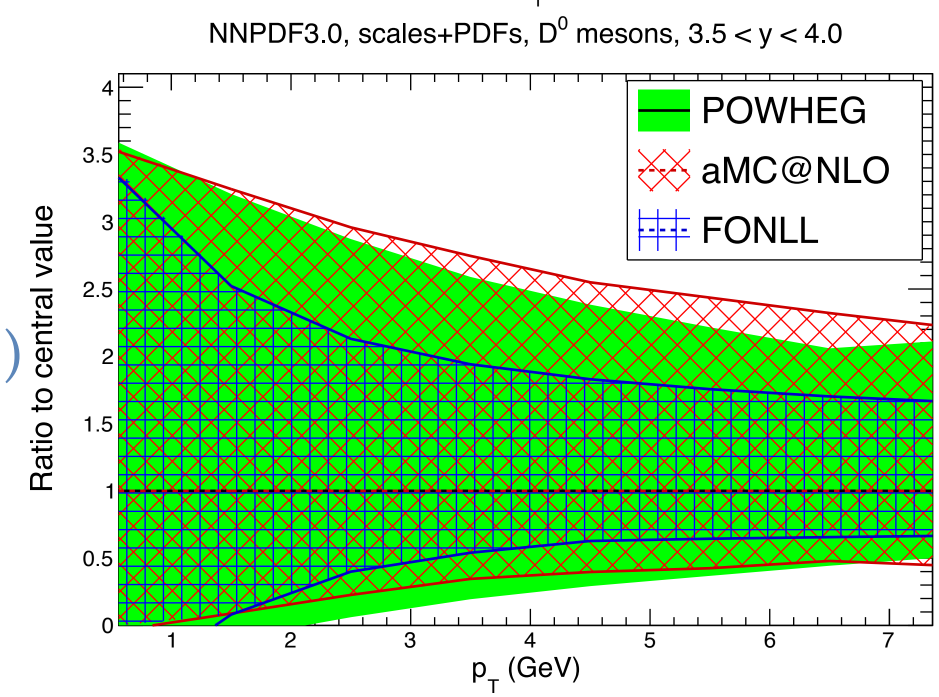




$$\sqrt{s} = 7\ [TeV]$$

arXiv:1506.08025

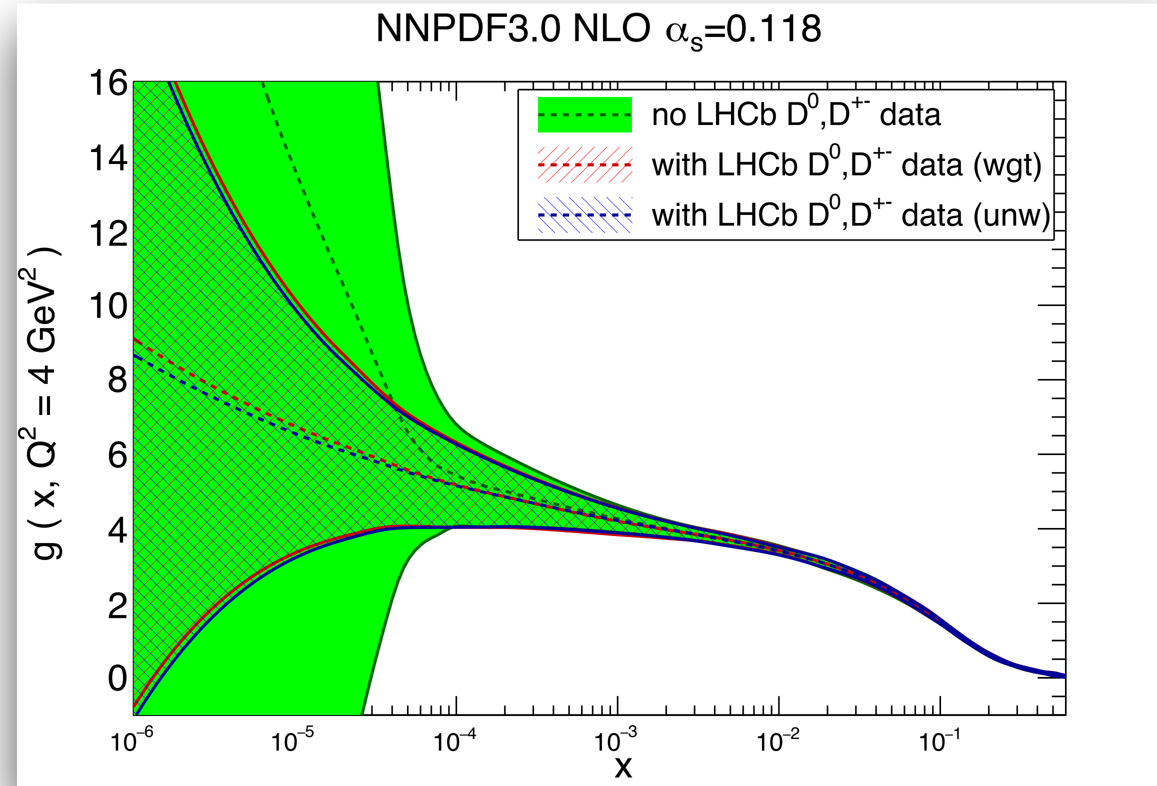
arXiv:1302.2864 (LHCb)

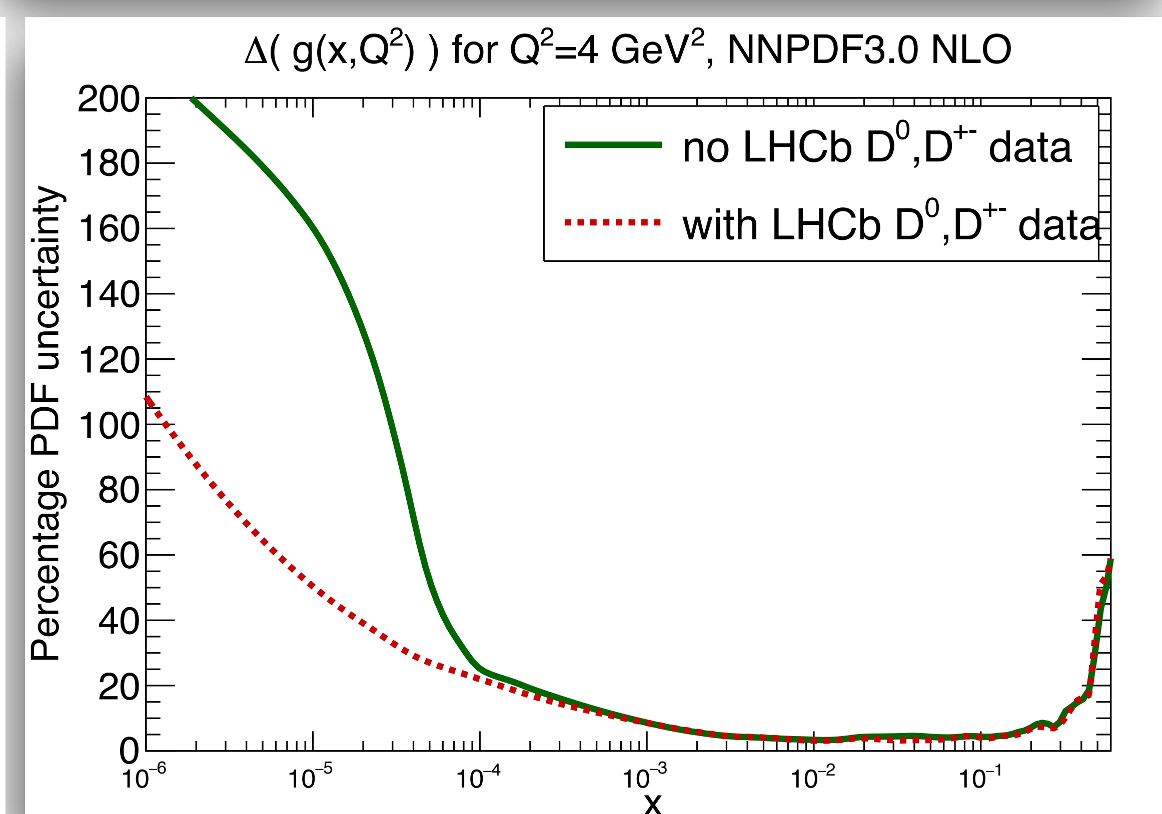


- We first **validate our NLO predictions** for forward charm production against recent LHCb data … finding g**ood agreement** between the 3 calculation schemes

Small-x gluon NNPDF: LHCb constraints

- We utilize charm production data from LHCb to **reduce the uncertainties in the small-x gluon PDF**
- By implementing a **Bayesian reweighing technique**, the impact of the new data is estimated … 75 data points added to NNPDF3.0 analysis
- The impact is negligible for $x > 10^{-4}$, but substantive in the smaller-x region where data was previously unavailable. At $x \sim 10^{-5}$, we achieve a **3x reduction in uncertainty**
- We utilize these improved PDFs to make **predictions for 13 TeV** physics, which were validated in *1510.01707 (LHCb)*

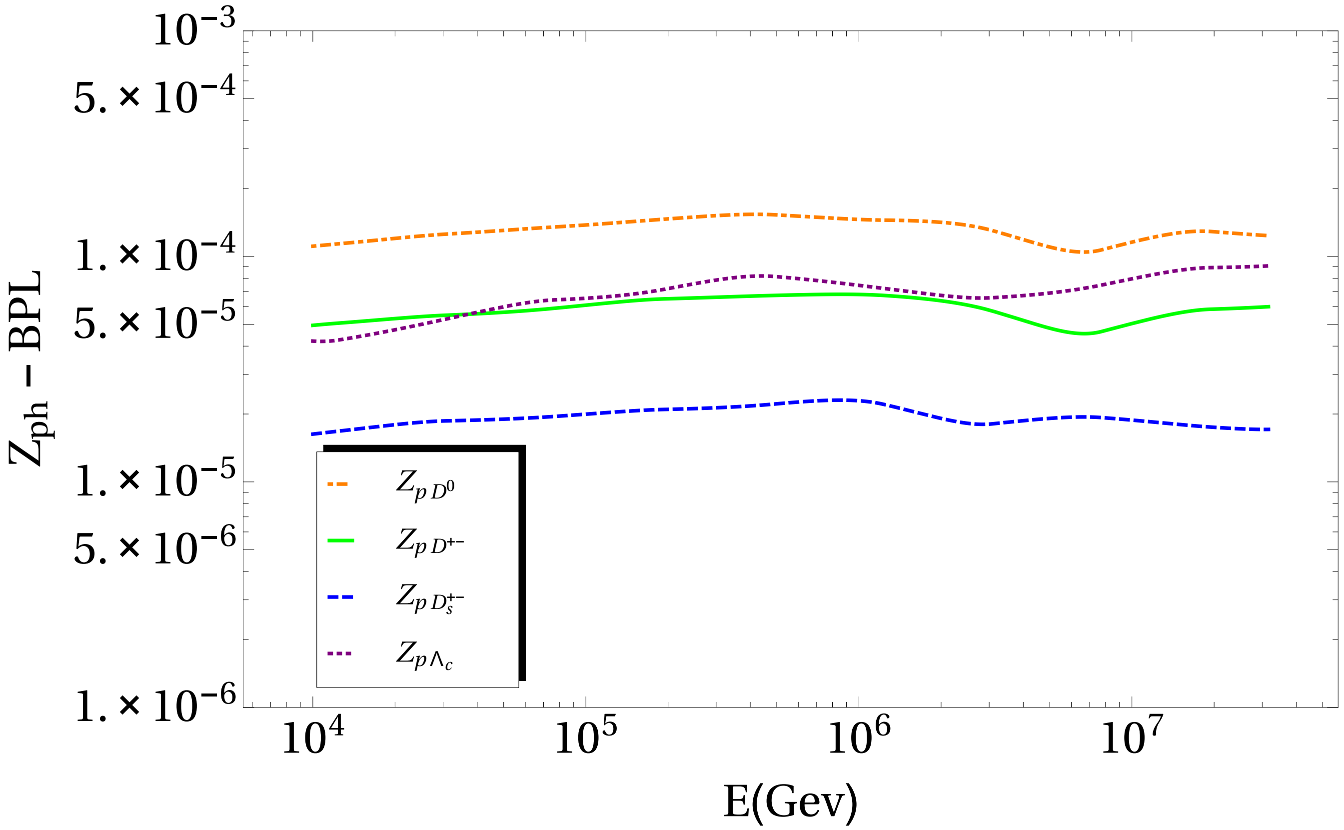


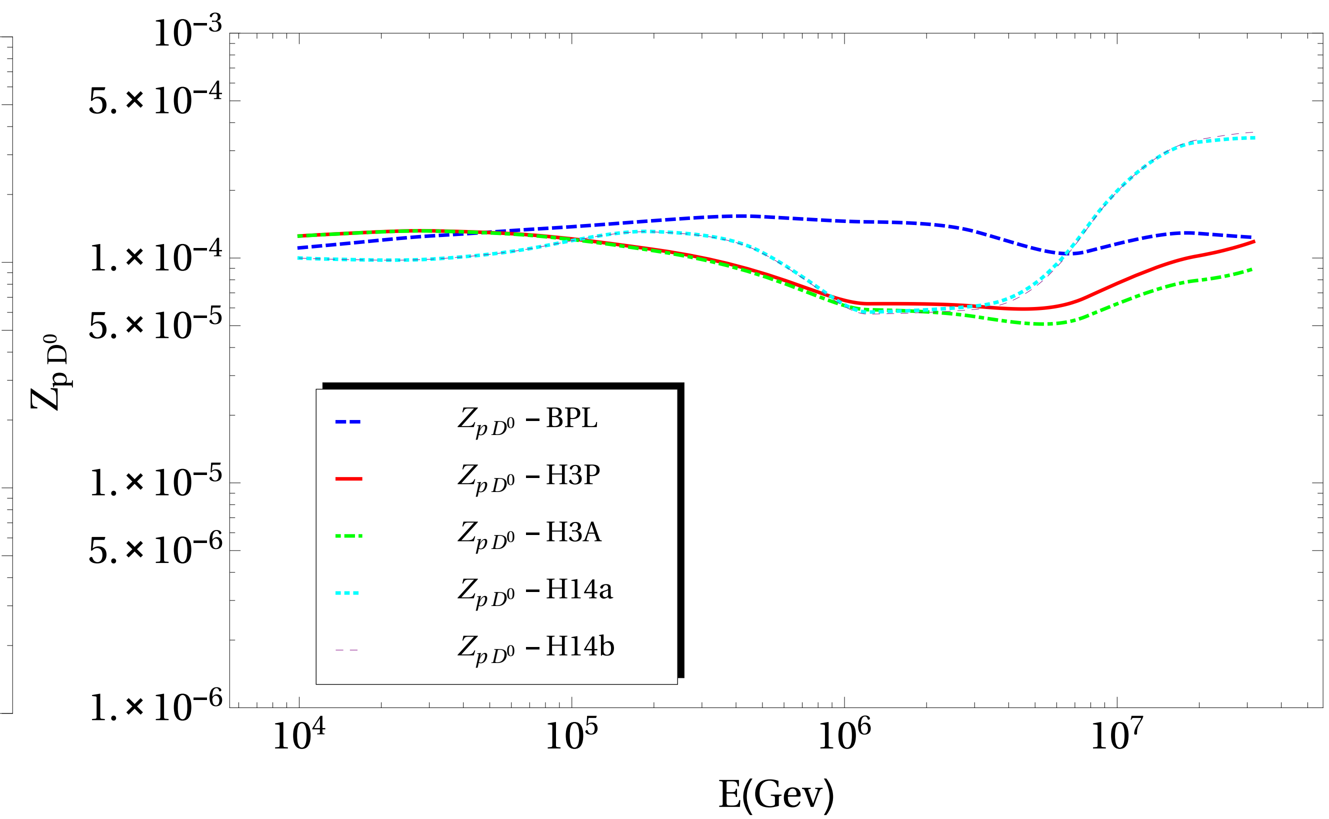


Z_{ph} with NNPDF3.0+LHCb

$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

- The differential cross-section is generated at various E' between 10^3 and $10^{10.5}$ GeV with **POWHEG+PYTHIA8**, and incorporates our updated **NNPDF3.0+LHCb** … Cross-checks made with aMC@NLO



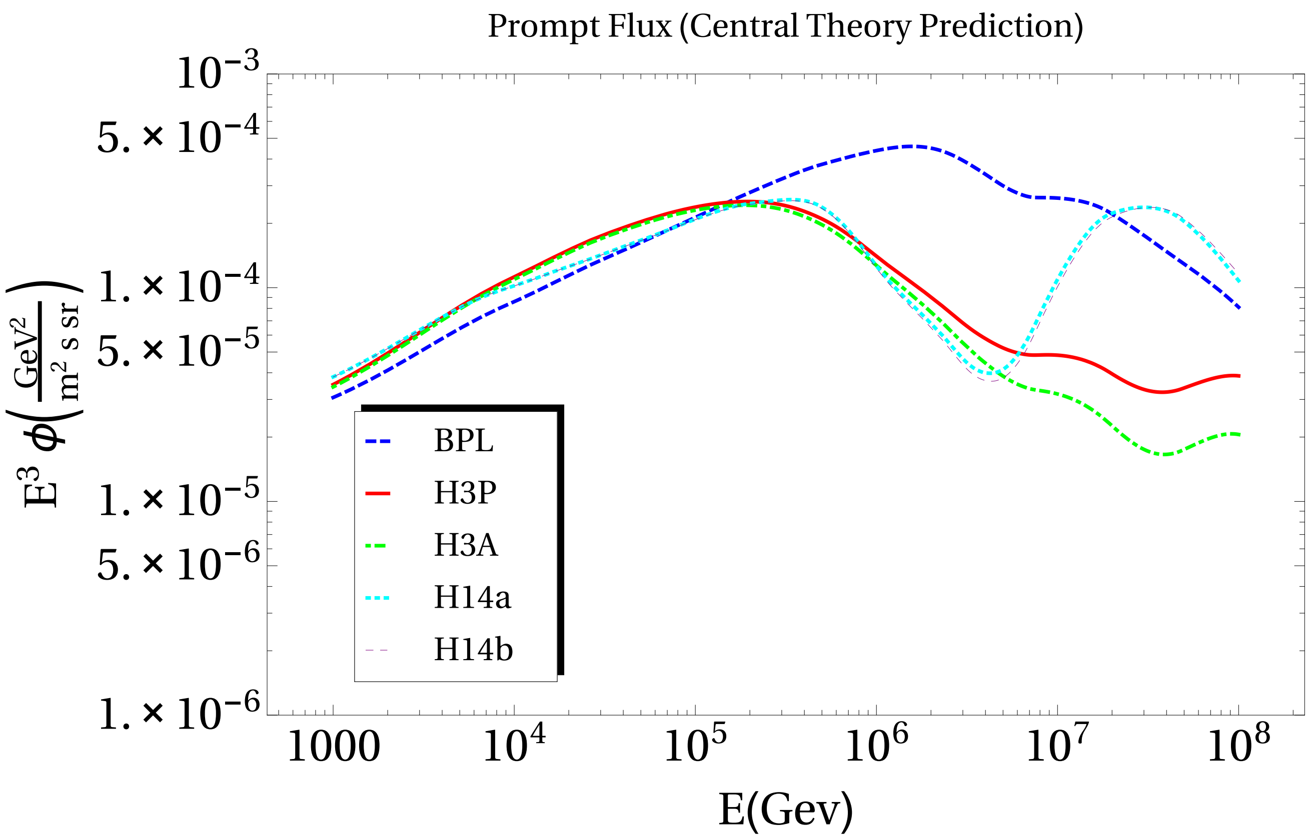


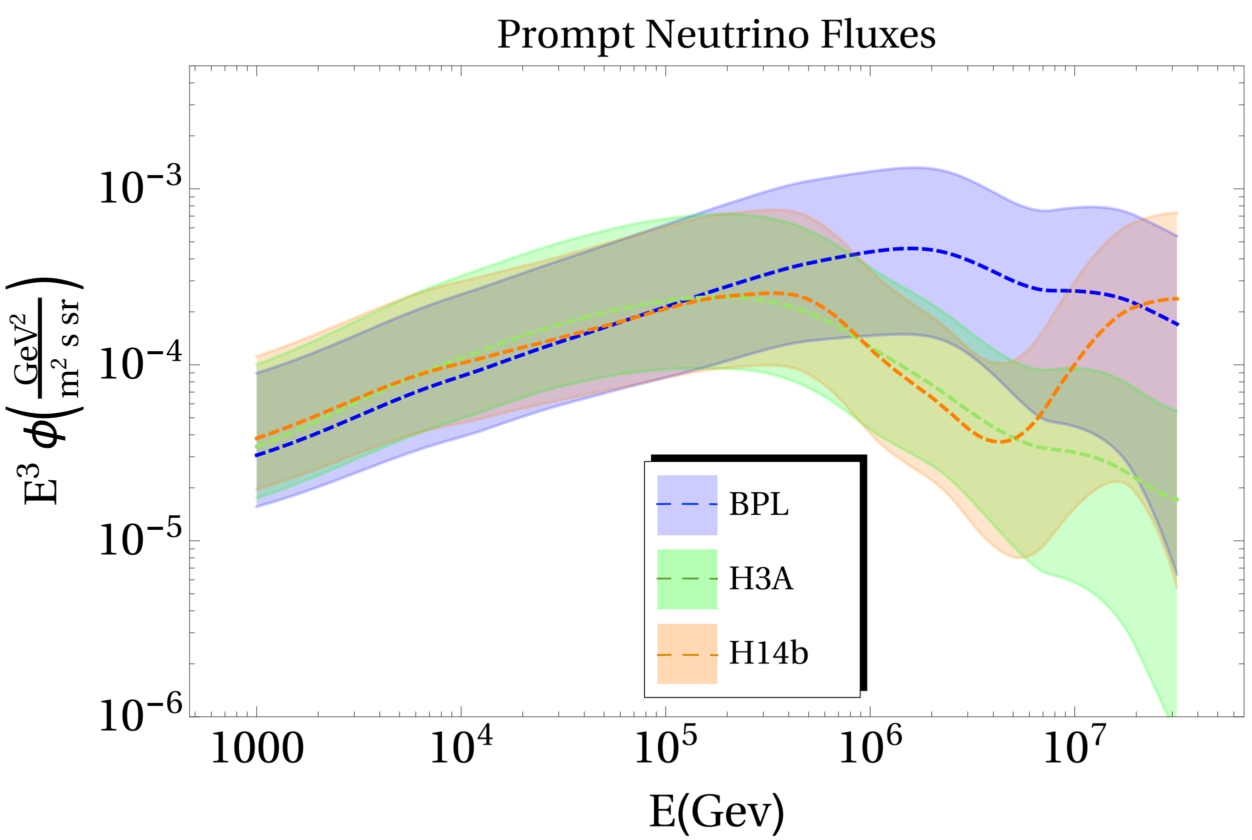
The relative contributions of different species in the BPL cosmic ray scenario.

The relative contributions of the D^0 species in varying cosmic ray scenarios.

Benchmark NNPDF3.0+LHCb flux

- We present the following predictions for **prompt atmospheric neutrino flux** adopting the broken power-law (BPL) as well as H3* and H14* cosmic-ray spectra



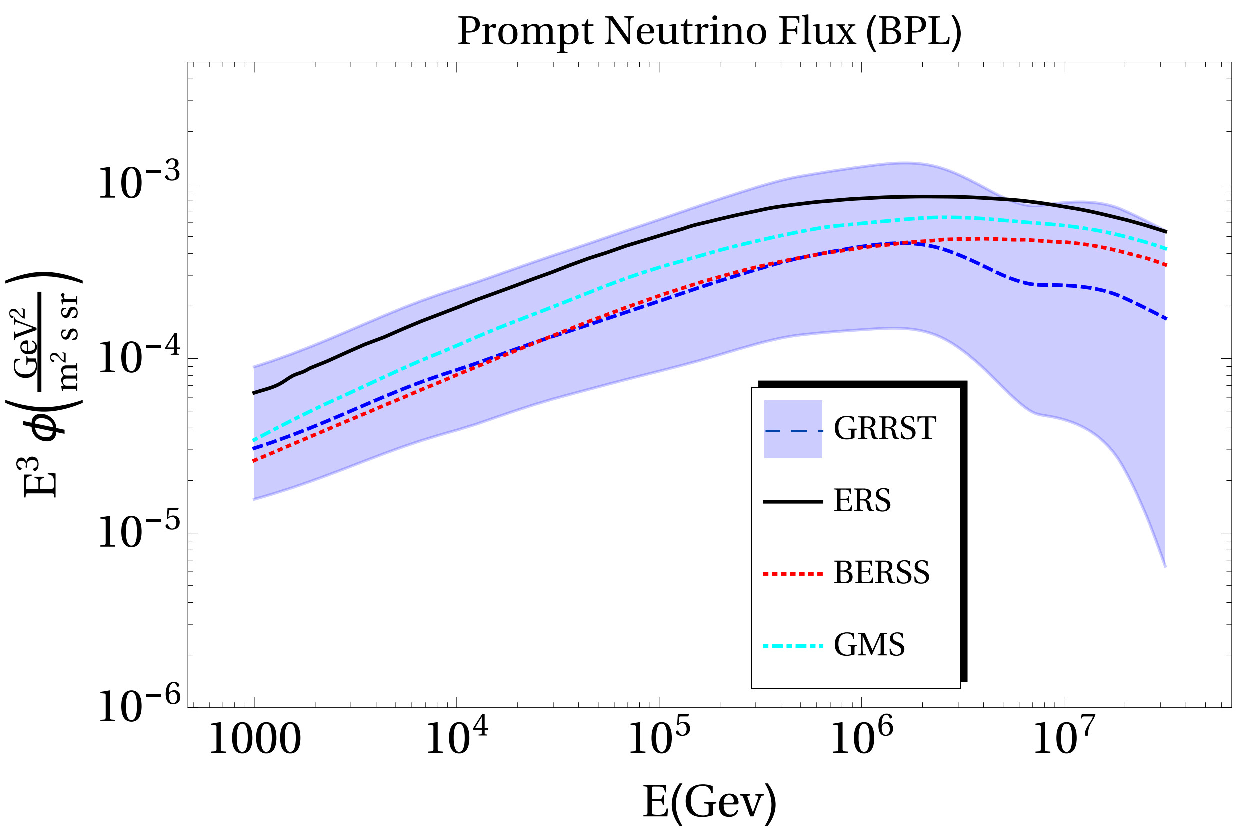


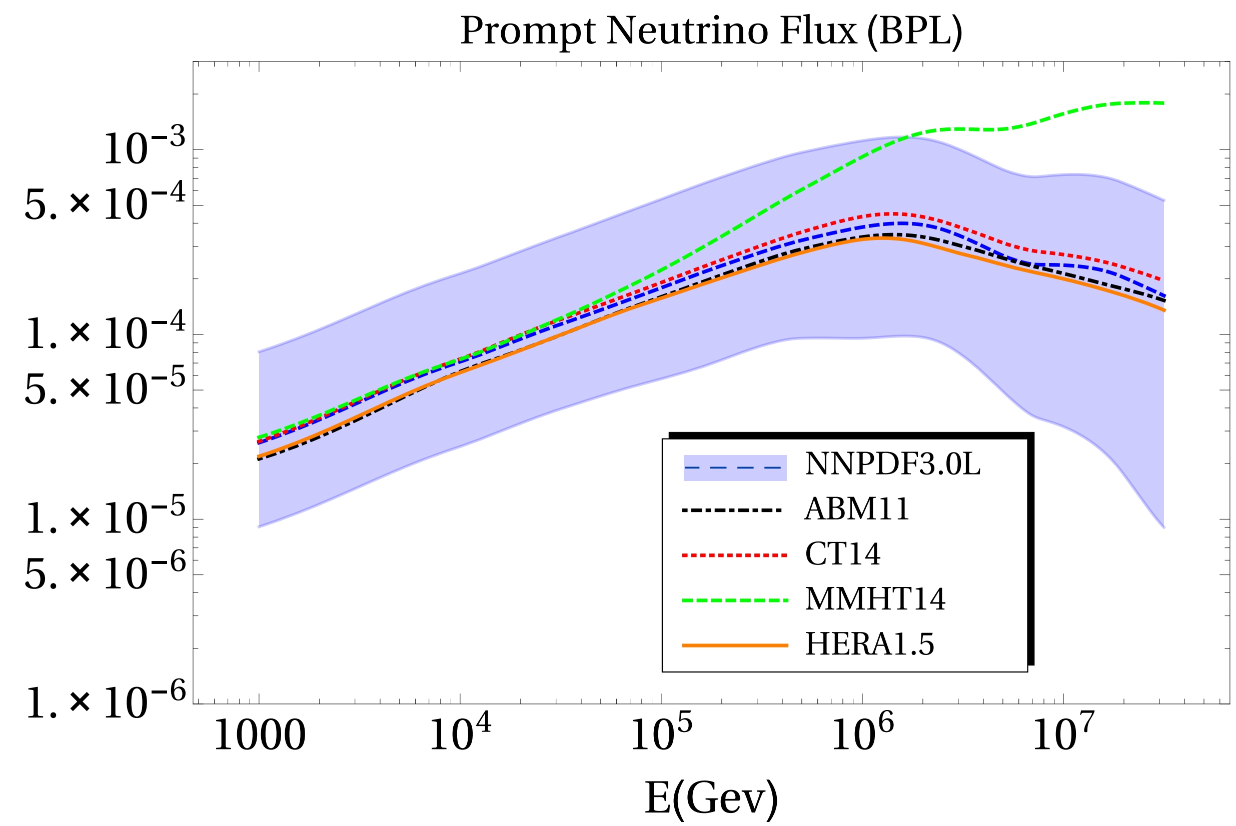
****Scale, PDF, and charm mass uncertainty****

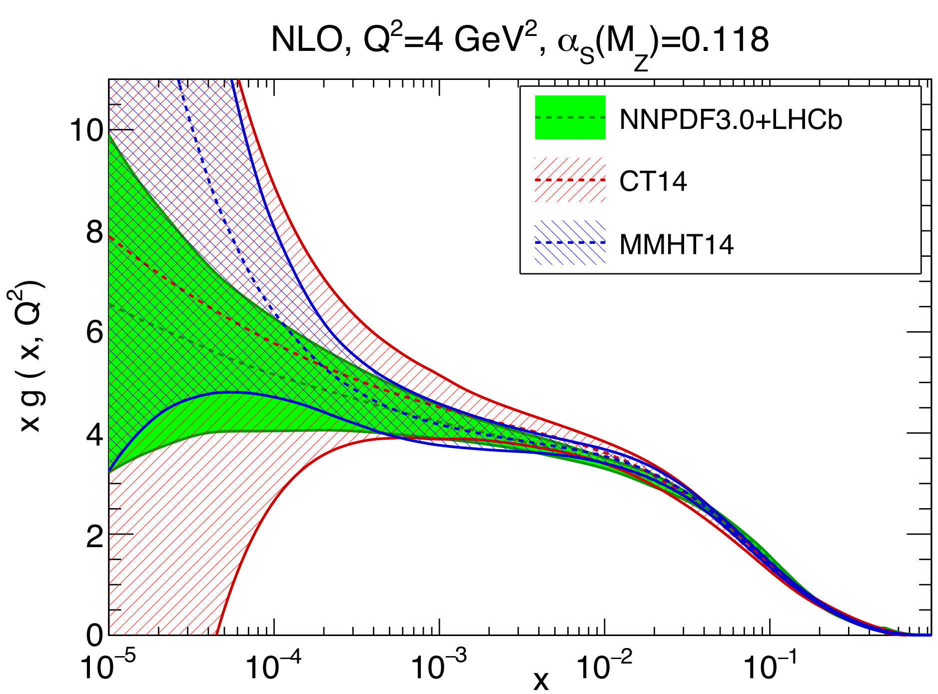
- Different cosmic ray spectrum parameterisations
- => **significant differences in the expected flux above ~100 TeV**

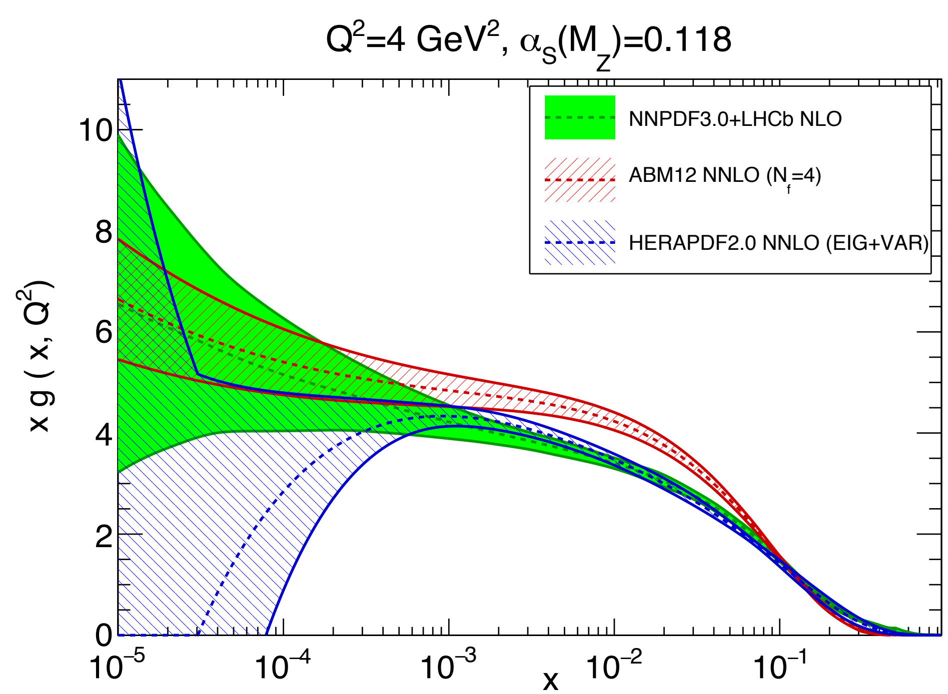
https://promptnuflux.hepforge.org

Consistency with others



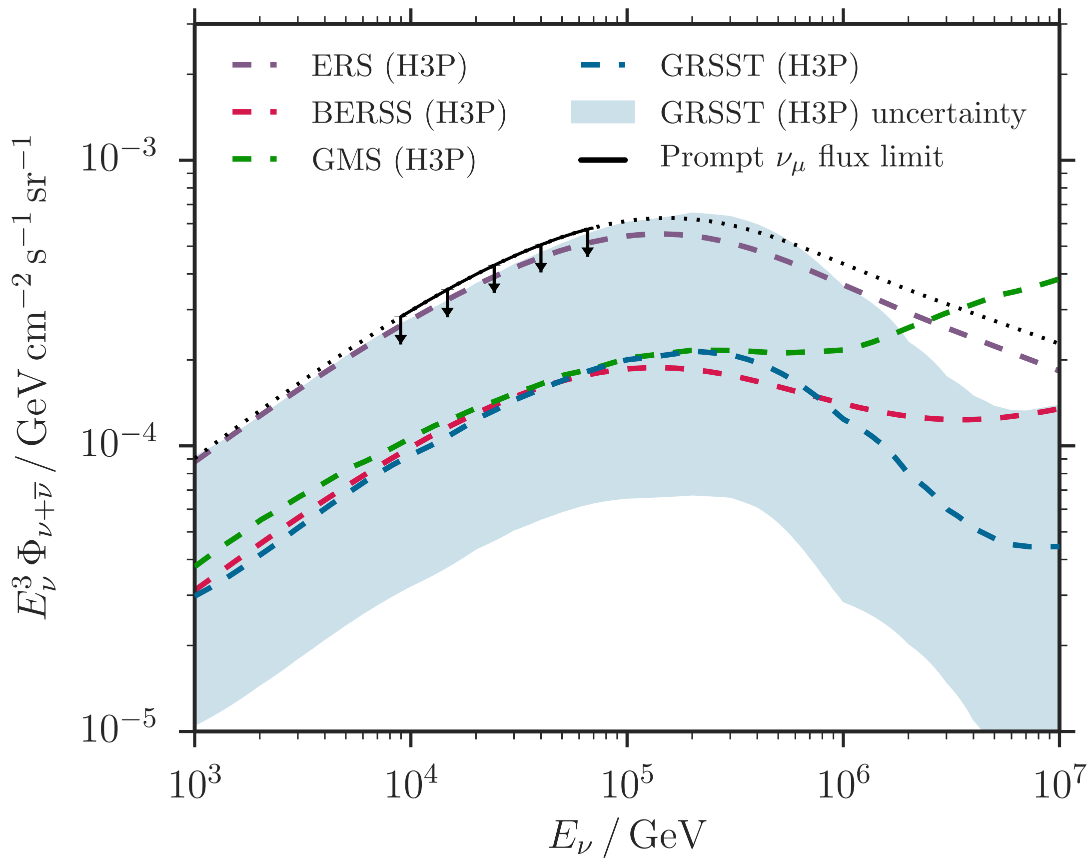






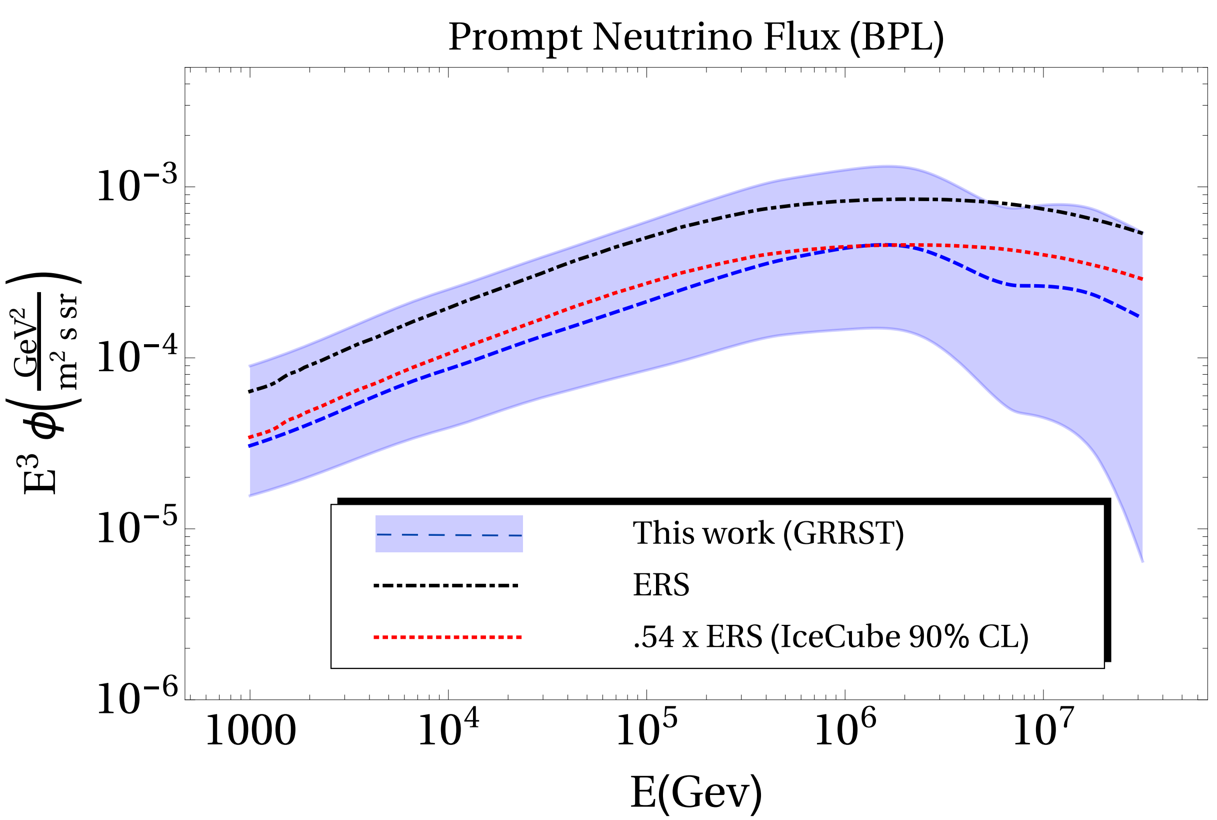
2016 IceCube limits

arXiv:hep-ph/1607.08006



Model	Flux limit
ERS (H3p)	1.06
GMS (H3p)	$\approx$ 2.9
BERSS (H3p)	$\approx$ 3.0
GRSST (H3p)	$\approx$ 3.1

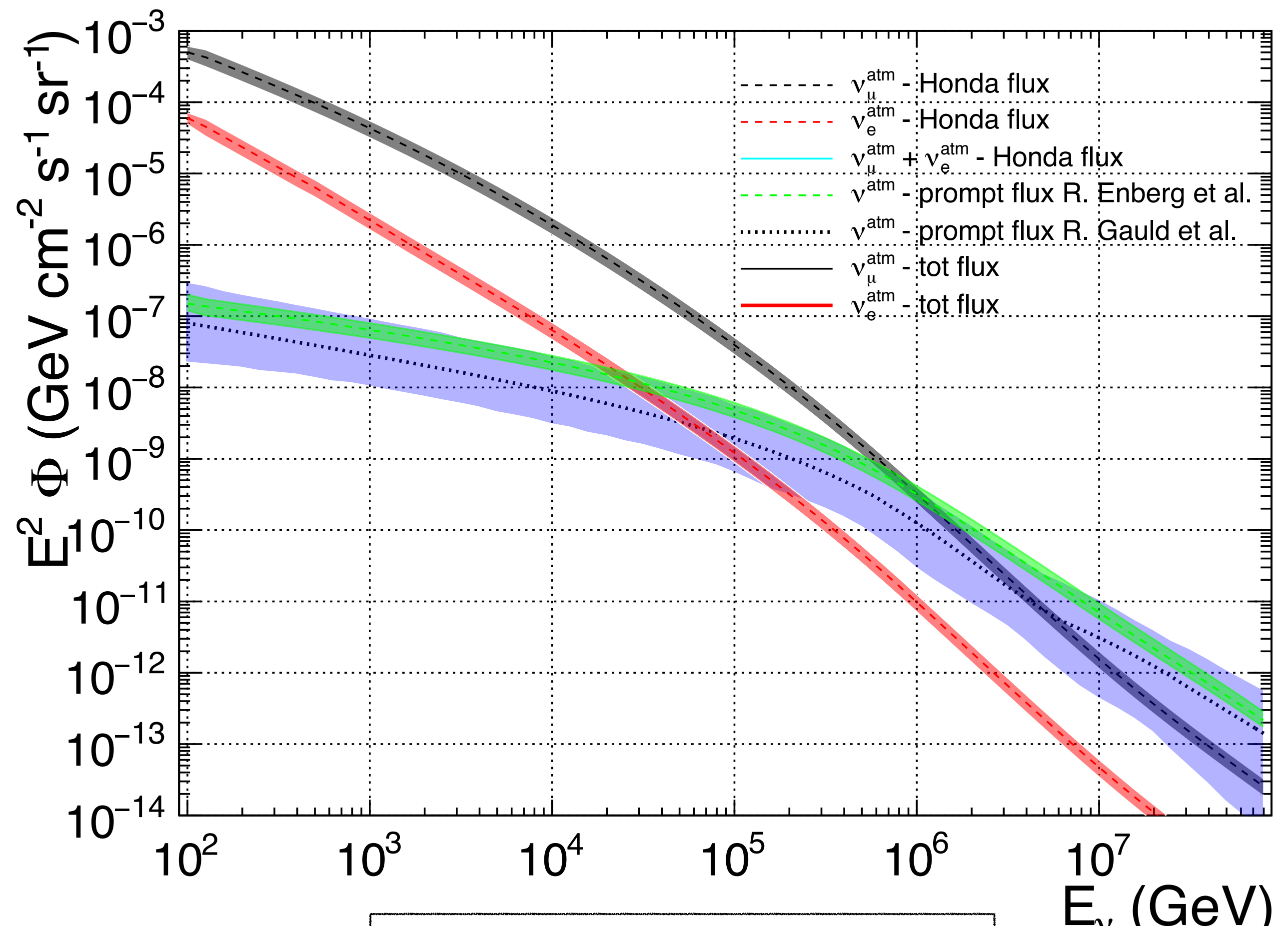
- Our central result is below the most recent IceCube bound, indicating that **a prompt component of the incoming flux should be observed soon**….



Intermediate conclusions

- We have presented updated predictions for the flux of **prompt atmospheric neutrinos** at ground-based detectors.
- Our approach is grounded in **perturbative QCD**, and incorporates:
    1. State-of-the-art calculation of **charmed hadron production** in the **forward region**, validated against recent LHCb measurements
    2. A **small-*x* gluon PDF** which is also constrained by LHCb data

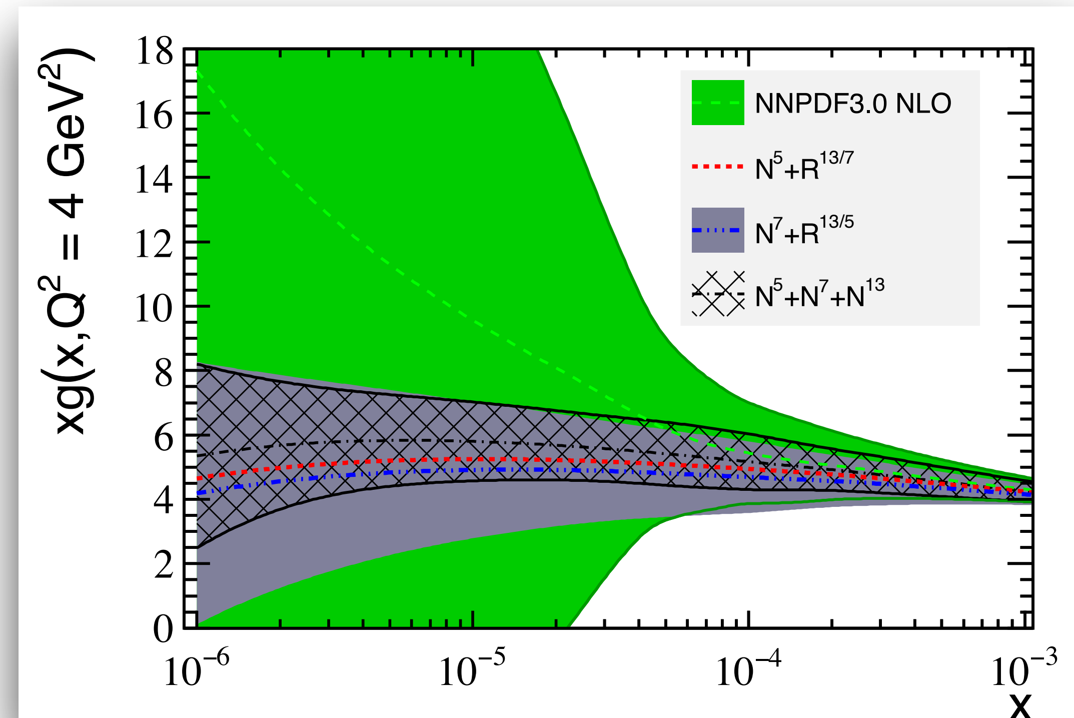
- Our estimates are consistent with previous studies but provide a **more reliable estimate of uncertainties** and alleviate potential tension between the previous benchmark (ERS) calculation and IceCube data.
- Results already being used for preliminary KM3Net *Letter of Intent*.

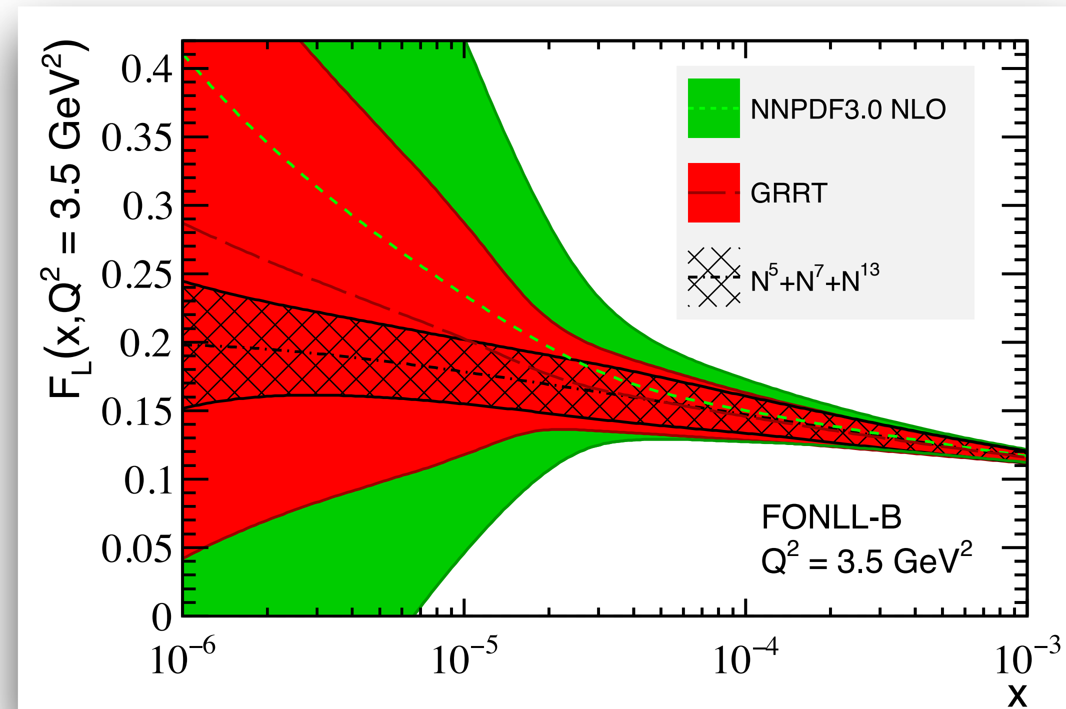


arXiv:hep-ph/1601.07549

Moving *forward*: PDF uncertainties

- Recently, **Gauld** and **Rojo** performed an even more precise fit for the gluon, using 5, 7 and 13 TeV data:





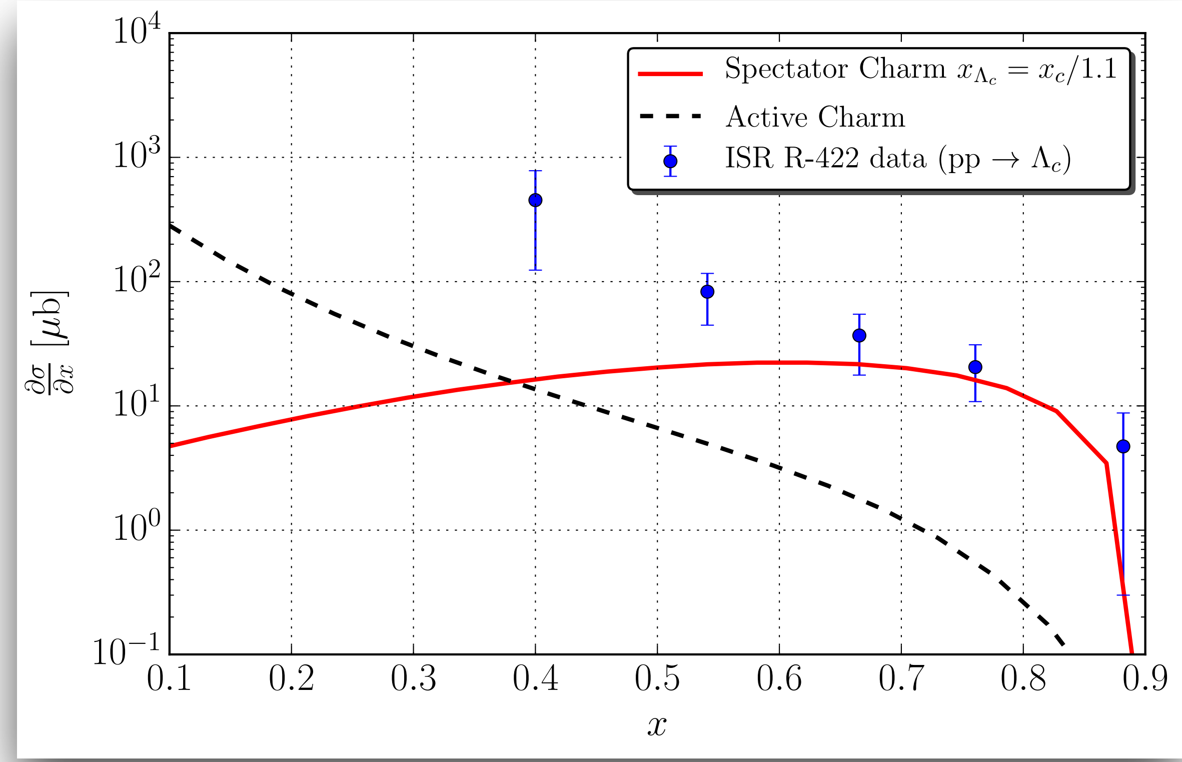
arXiv:hep-ph/1610.09373

- But the bulk of our **uncertainty bands are due to scales**, across the breadth of the relevant energy spectrum…

- **NNLO results for charm production** will be the key to reduced uncertainties!

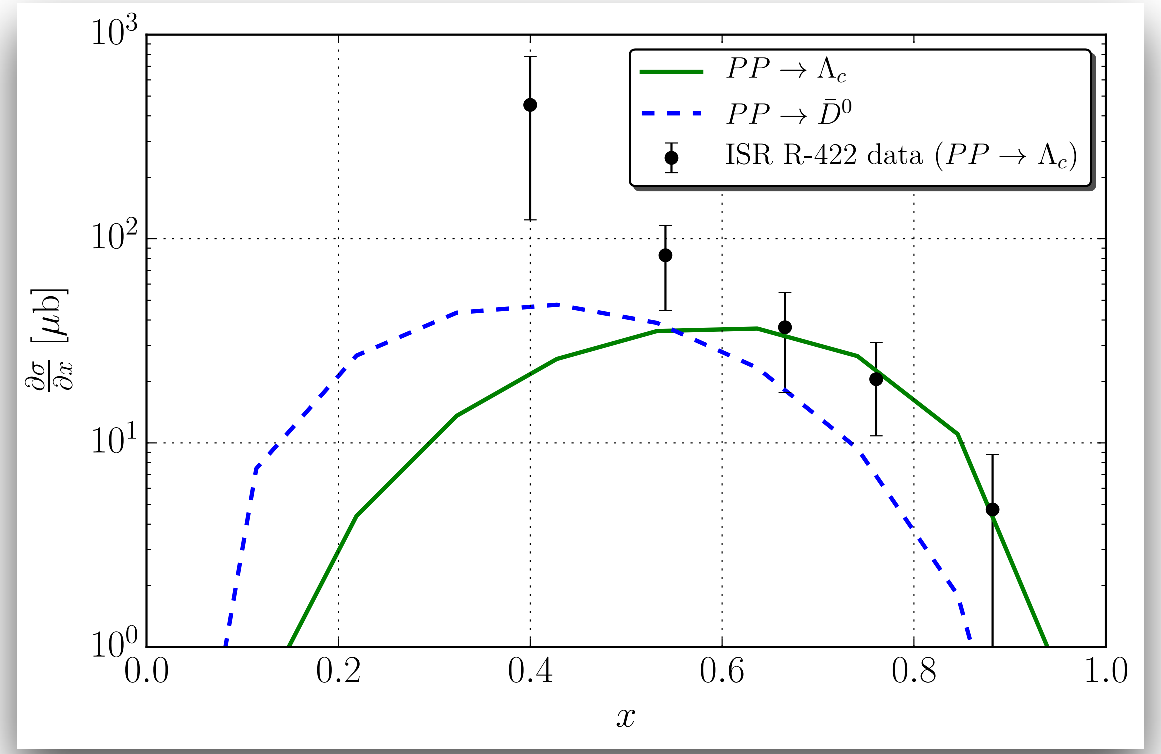
Moving *forward*: charm production

- Our results are for the ***central*** production of charm ($x_F \sim 0$).
- Motivated by strange particle production at high x_F, **Halzen** and **Wille** have attempted to put bounds on the **ultra-forward** component of charm.
- In one study they implement a spectator-charm model, and in another they parameterize the cross-section in a model-independent way. In both, normalization is given by **ISR** data.



'spectator-charm'

arXiv:hep-ph/1601.03044

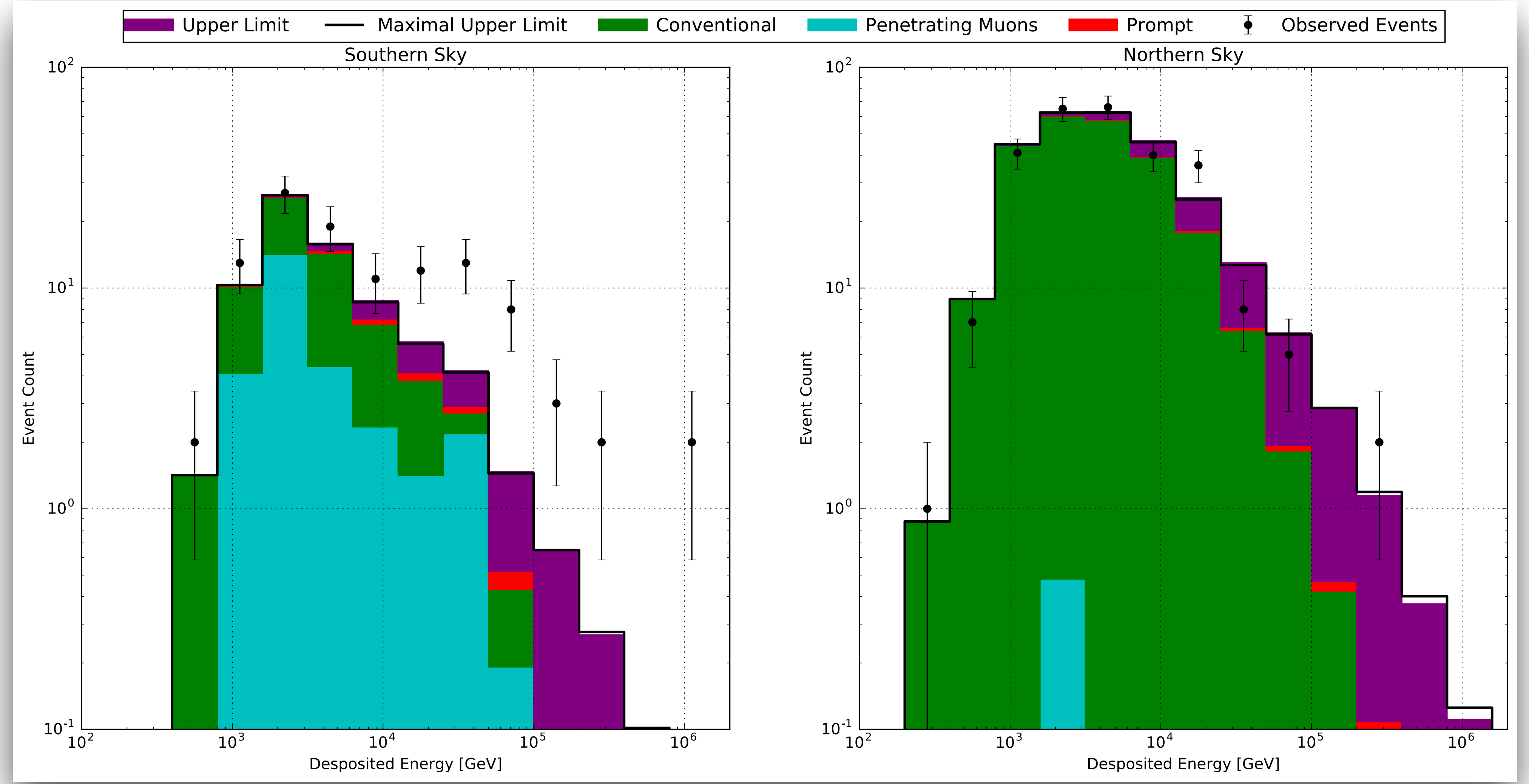


'model-independent'

arXiv:hep-ph/1605.01409

Moving *forward*: charm production

- Regardless, Halzen and Wille find that the forward contribution is still **insufficient** to accommodate the observed neutrino excesses:



arXiv:hep-ph/1605.01409

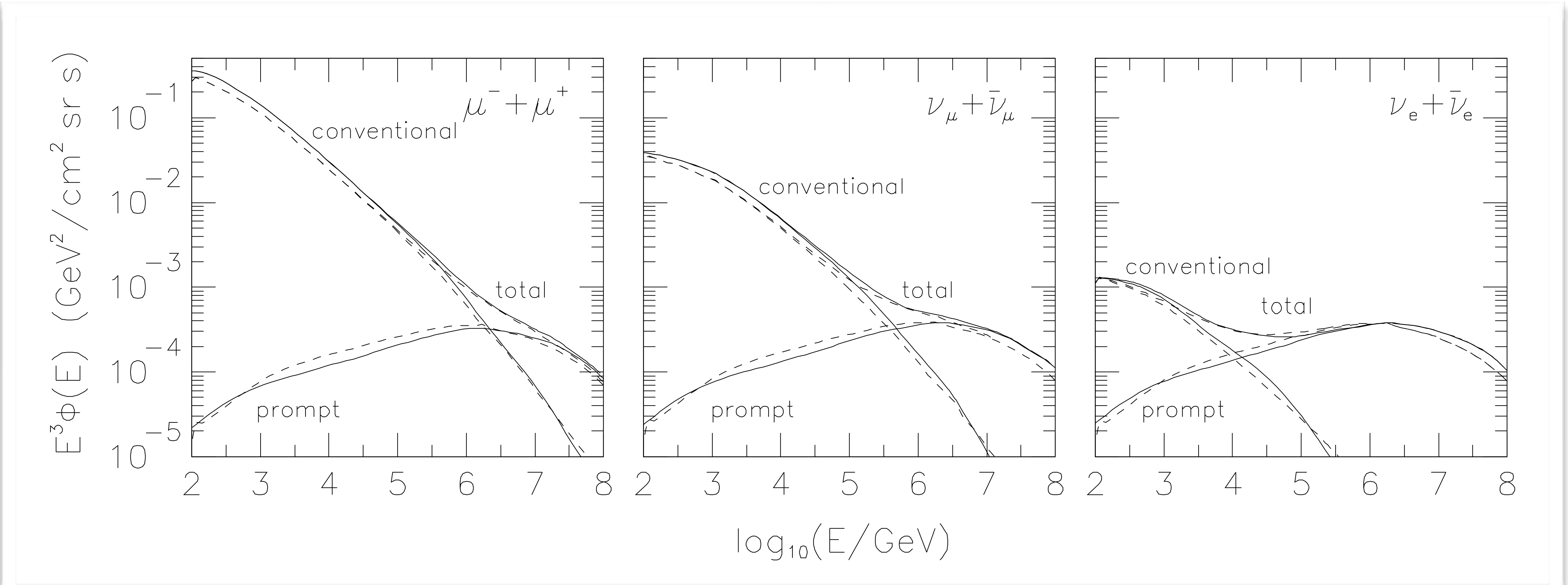
Is there a more reliable way to calculate the forward contribution?

- Also note the intrinsic charm analysis of Brodsky et al: 1607.08240!

Moving *forward*: systematics

- As the charm hadroproduction has been validated by LHCb, a non-observation of the prompt component at IceCube may signal a **deficiency in the cascade formalism**…

- We can utilize our distributions for charm production in other codes, but should we expect any significant differences?



arXiv:9505417 (Gondolo et al.)

Final conclusions

- The exciting discovery of cosmic neutrinos at IceCube marks the beginning of neutrino astronomy.
- However, backgrounds from atmospheric neutrinos are key to understanding and calibrating the observed spectrum.
- Prompt atmospheric neutrinos mimic the similarly hard spectrum of their cosmic cousins, but their production is highly uncertain due to QCD and other systematics. To date, no prompt neutrinos have been observed at IceCube.
- More work is needed to understand both perturbative and non-perturbative aspects of charm hadroproduction. What new tools can we utilize to study the ultra-forward region, e.g.?

The prompt flux should be seen *soon* (and provide a probe of low-x QCD)